SIMILAR RELATIVE DECLINE IN AEROBIC AND ANAEROBIC POWER WITH AGE IN ENDURANCE AND POWER MASTER ATHLETES OF BOTH SEXES

Bagley L[1], McPhee JS[2], Ganse B[3], Müller K[4], Korhonen MT[5], Rittweger J[4,6], Degens H[1,7,8]

[1]: School of Healthcare Science, Manchester Metropolitan University, Manchester, UK; [2]: Department of Sport and Exercise Sciences, Manchester Metropolitan University, Manchester, UK; [3]:Department of Orthopaedic Trauma; RWTH Aachen University Hospital; Aachen; Germany; [4]: Institute of Aerospace Medicine; German Aerospace Center; Cologne; Germany; [5]: Gerontology Research Center; Faculty of Sport and Health Sciences; University of Jyväskylä; Finland; [6]: Department of Pediatrics and Adolescent Medicine, University of Cologne, Cologne, Germany, [7]: Institute of Sport Science and Innovations; Lithuanian Sports University; Kaunas; Lithuania, [8]: University of Medicine and Pharmacy of Targu Mures, Rumania

Running title: Anaerobic and aerobic power in master athletes

Address for correspondence:

Dr L. Bagley

School of Healthcare Science

Manchester Metropolitan University

M1 5GD, Manchester

UK

Tel: +441612471145

E-mail: Liam.Bagley@mmu.ac.uk

ABSTRACT

Lower physical activity levels in old age are thought to contribute to the age-related decline in peak aerobic and anaerobic power. Master athletes maintain high levels of physical activity with advancing age and endurance or power training may influence the extent to which these physical functions decline with advancing age. To investigate, 37-90-year-old power (n=20, 45% female) and endurance (n=19, 58% female) master athletes were recruited. Maximal aerobic power was assessed when cycling two-legged ($VO_2Peak_{2\text{-}leg}$) and cycling one-legged ($VO_2Peak_{1\text{-}leg}$), while peak jumping (anaerobic) power was assessed by a countermovement jump. Men and women had a similar $VO_2Peak_{2\text{-}leg}$ ($mL \cdot kg^{-1} \cdot min^{-1}$, $p=0.138$) and similar ratio of $VO_2Peak_{1\text{-}leg}$ to $VO_2Peak_{2\text{-}leg}$ ($p=0.959$) and similar ratio of peak aerobic to anaerobic power ($p=0.261$). The $VO_2Peak_{2\text{-}leg}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) was 17% ($p=0.022$) and the peak rate of fat oxidation (FATmax) during steady-state cycling was 45% higher in endurance than power athletes ($p=0.001$). The anaerobic power was 33% higher in power than endurance athletes ($p=0.022$). The $VO_2Peak_{1\text{-}leg}$:$VO_2Peak_{2\text{-}leg}$ ratio did not differ significantly between disciplines, but the aerobic to anaerobic power ratio was 40% higher in endurance than power athletes ($p=0.002$). Anaerobic power, $VO_2Peak_{2\text{-}leg}$, $VO_2Peak_{1\text{-}leg}$ and power at FATmax decreased by around 7-14% per decade in male and female power and endurance athletes.

The cross-sectional data from 37-90-year-old master athletes in the present study indicates that peak anaerobic and aerobic power decline by around 7-14% per decade and this does not differ between athletic disciplines or sexes.

Key words: master athletes, ageing, fatty acid oxidation, VO_2Peak

Introduction

Ageing is accompanied by a progressive decline in bodily functions, ultimately resulting in death [1]. Such age-related decrements include a decrease in muscle mass, strength and power generating capacity [2], and reductions in aerobic fitness [3]. Similar changes are also seen during disuse [4]. It is thus likely that the reduction in physical activity in old age [5] contributes significantly to the age-related reduction in muscle power and maximal oxygen uptake.

Master athletes maintain high levels of physical activity into old age [6] and show impressive athletic feats [7] such as a 97-year-old man still cycling 5,000 km a year [8]. They have better physiological function [9], longer lifespan, lower hospitalisation [10] and better quality of life in comparison to sedentary people of the same age [11]. Thus, regular exercise helps to combat the effects of ageing [12] and this provides an opportunity to distinguish the effects of ageing *per se* from the age-related reductions in physical activity [7].

Low cardiopulmonary fitness and neuromuscular function, and high body fatness are common features of ageing and risk factors for disability and all-cause mortality [13, 14]. These changes are not only due to low activity levels, since even in master athletes, performance levels, cardiopulmonary fitness and neuromuscular function decline [15-18]. However, endurance and power training impose different stresses upon cardiopulmonary and neuromuscular systems, with for instance higher ground reaction forces produced during higher running speeds such as when sprinting [19, 20].

It remains unknown whether the characteristics that determine power performance, such as very high peak muscle power, decline with ageing at different rates from those that determine endurance performance, such as high cardiopulmonary fitness and muscle aerobic potential. Given that endurance and power training promote divergent adaptations, such as increased skeletal muscle cross-sectional area and power in power athletes [21], and increased cardiorespiratory fitness, oxidative and fat oxidation capacity in endurance athletes [22, 23], we hypothesised that the anaerobic power is better preserved during ageing in power than endurance athletes, while the aerobic and fat oxidation capacity is better preserved in endurance athletes.

Methods

Participants

The study conformed to the latest revisions of the Declaration of Helsinki [24] and was approved by the Ärztekammer Nordrhein ethics committee, Düsseldorf, Germany (number 2012157). Volunteers were recruited and assessed at the 18th European Veterans Athletics Championships (EVACs) at Weinau Stadium, Zittau, Germany between 16-25 August 2012.

Volunteers provided written informed consent prior to participation. Those with a history of cardiovascular, neuromuscular or metabolic disease, or those who had a leg fracture in the past two years were excluded from the study. Participants were grouped into endurance and power disciplines by their primary entered events. Running events ≥800 m were classified as endurance, and ≤400 m and throwers were classified as power athletes (according to IAAF classifications: https://www.iaaf.org/disciplines). The age-graded performance for the main event of each athlete was calculated using the World Master Athletics age-grading calculator: http://www.howardgrubb.co.uk/athletics/wmalookup06.html. Participant characteristics are shown in Table 1.

Experiments

Peak jumping (anaerobic) power: Peak jumping power as a measure of peak anaerobic power [20] was assessed in 29 athletes on a Leonardo force platform (Novotec Medical, Pforzheim, Germany). The participants were instructed to perform a two-legged countermovement jump with the aim to raise the head and trunk as far as possible while freely moving their arms. Participants made two or three submaximal jumps to acquaint themselves with the procedure. They then performed three maximal efforts, each separated by 60 s rest and the attempt that gave the highest power (W) was recorded. The system computed the take-off velocity from the ground reaction force as described by Cavagna [25]. Instantaneous power was calculated as the product of force and velocity: Power (W) = Force (N) x Velocity ($m \cdot s^{-1}$).

$VO_2Peak_{2\text{-}leg}$ (aerobic power): $VO_2Peak_{2\text{-}leg}$ was determined on a cycle ergometer (Jaeger Ergocycle) with a MetaLyzer 3B - R2 (Cortex BioPhysik GmbH, Leipzig, Germany) to measure VO_2 and VCO_2. Participants started to cycle at a workload of 50 W and a cadence of 70 rpm.

Workload was increased every 3 min with 50 W for men and 30 W for women until the respiratory exchange ratio was higher than 1.0 for at least 1 min. From this point onwards, workload was increased by 20 W every minute until the age-predicted HRmax (220 – age) was exceeded, if the participant reached volitional exhaustion and/or the respiratory exchange ratio was >1.1. Heart rate was measured using a Polar heart rate monitor (Polar Oy, Kempele, Finland). The assessment was followed by a 5-min cool down at low cadence (~40 rpm) and workload (25-75 W). The average of the values in the last 30 seconds of the last step was taken as the $VO_2Peak_{2\text{-leg}}$. The maximal workload during the test was presented as maximal aerobic power.

FATmax (maximal fatty acid oxidation): The rate of fatty acid oxidation was estimated for each workload as described previously [26]:

$$\textit{Rate of Fatty Acid Oxidation } (g\cdot min^{-1}) = (1.695 \times VO_2) - (1.701 \times VCO_2)$$

Where VO_2 and VCO_2 are given in $L\cdot min^{-1}$ and negligible urinary nitrogen excretion is assumed. FATmax was calculated by fitting the rate of fatty acid oxidation *vs.* $\%VO_2peak_{2\text{-leg}}$ with a polynomial, where the peak of the line was considered the maximal rate of fatty acid oxidation.

$VO_2Peak_{1\text{-leg}}$: The $VO_2Peak_{1\text{-leg}}$ during one-leg cycling was measured on a separate day from all other assessments in a subgroup of 18 participants with the same equipment and calibrations as the $VO_2Peak_{2\text{-leg}}$ assessment. This assessment was included to estimate the peak aerobic capacity of the active leg muscles. Where $VO_2Peak_{2\text{-leg}}$ may be limited by the cardio-respiratory supply of oxygen to the working muscles and/or by the uptake and utilisation of available oxygen within muscle fibres[27, 28], the cardio-respiratory supply of oxygen to active leg muscles during one-legged cycling is not generally limiting. Therefore, the $VO_2Peak_{1\text{-leg}}$ more closely represents the leg muscle peak aerobic potential[29] .
For this assessment, the dominant leg was secured to the pedal on the cycle ergometer, while the non-exercising leg was positioned on a central platform on the cycle ergometer to limit extraneous movements. The participants were asked to minimise upper body movement during the exercise. The workload began at 20 W at 70 rpm for the first two minutes of the test, after which the workload was increased to 50 W for one minute and then by 10 W per minute until volitional exhaustion or a cadence of 70 rpm could not be maintained. The

$VO_2Peak_{1\text{-leg}}$ ($L \cdot min^{-1}$) was taken as the highest value of 30 s rolling averages, which in all cases occurred during the final minute of exercise.

Statistical analysis

Data were analysed using SPSS (v.24 IBM). A two-factor ANOVA was used with sex and athletic discipline (power *vs*. endurance) as between-factors. A discipline*sex interaction indicates that the effect of athletic discipline differs between men and women, determined by an additional post hoc independent samples t-test. A stepwise linear regression was performed with factors age, sex and discipline to assess the impact of these variables on the outcome measures, with adjusted R-values presented. Age-related changes in ratios of jumping power to $VO_2Peak_{2\text{-leg}}$, FATmax and the ratio of $VO_2Peak_{1\text{-leg}}$: $VO_2Peak_{2\text{-leg}}$ were also analysed by this method. Statistical significance was accepted at $p<0.05$. Data are presented as mean (±SEM) unless stated otherwise.

Results

Participant characteristics

Participant characteristics are shown in Table 1. There was no significant difference in the age of the endurance and power athletes. Men were taller and had a larger body mass than women ($p<0.001$). The body mass of the power athletes was larger than that of endurance athletes ($p=0.001$). The BMI was higher in power than endurance athletes ($p=0.001$), but did not differ significantly between men and women ($p=0.061$). The AGP did not differ significantly between athletic discipline or between the sexes ($p=0.973$ and $p=0.718$, respectively).

Jumping (anaerobic) power

Men achieved a 64% higher jumping power than women (Table 2; $p=0.002$). However, when normalised to body mass, there was no longer a difference between the sexes in peak jumping power (Table 2; $p=0.070$). Power athletes achieved 58% higher power during vertical jumps compared with long distance runners (Table 2; $p=0.003$) and 33% higher power than distance runners when normalised to body mass (Table 2; $p=0.022$). The take-off velocity from the jump was 19% higher in men than women (Table 2; $p=0.004$), and was 15% higher in power than endurance athletes (Table 2; $p=0.027$).

$VO_2Peak_{2\text{-}leg}$

Men displayed a 38% higher $VO_2Peak_{2\text{-}leg}$ ($L \cdot min^{-1}$) than women (Table 2; $p=0.001$), but this difference disappeared when normalised to body mass ($mL \cdot kg^{-1} \cdot min^{-1}$) (Table 2; $p=0.138$). $VO_2Peak_{2\text{-}leg}$ ($L \cdot min^{-1}$) did not differ significantly between power and endurance athletes (Table 2; $p=0.592$), but when expressed per body mass it was 17% higher in endurance athletes (Table 2; $p=0.022$). Power (W) at $VO_2Peak_{2\text{-}leg}$ was 37% higher in men than women ($p=0.024$), but did not differ between power and endurance athletes ($p=0.817$).

FATmax

There was a sex * discipline interaction for FATmax ($g \cdot min^{-1}$: $p=0.027$; $mg \cdot kg \cdot min^{-1}$: $p=0.019$) which was reflected by a higher FATmax ($mg \cdot kg \cdot min^{-1}$) in endurance than power athletes in men ($p<0.001$), but not in women ($p=0.529$) and a similar FATmax ($mg \cdot kg \cdot min^{-1}$) in male and female endurance athletes ($p=0.121$) and male and female power athletes ($p=0.067$) (Table 2; Figure 1). There were no effects of sex ($p=0.964$) or discipline ($p=0.144$) on the percentage of $VO_2Peak_{2\text{-}leg}$ at which FATmax occurred.

$VO_2Peak_{1\text{-}leg}$ ($L \cdot min^{-1}$)

$VO_2Peak_{1\text{-}leg}$ was similar in men and women ($p=0.159$), and in endurance and power athletes ($p=0.431$). During the single-leg cycling tests, HR_{Peak} reached 86±1% and 81±1% ($p=0.433$) of the values achieved during two-leg cycling for power and endurance athletes, respectively, with no difference between sexes ($p=0.252$). Power (W) at $VO_2Peak_{1\text{-}leg}$ was not significantly different between sexes or disciplines whether normalised to body mass or not ($p>0.05$ in all cases). The ratio of $VO_2Peak_{1\text{-}leg}$ to $VO_2Peak_{2\text{-}leg}$ did not differ significantly between disciplines ($p=0.404$) or sexes ($p=0.959$).

Ratio of aerobic to anaerobic power

There was no significant difference ($p=0.261$) between men (7.1±0.5%) and women (8.4±0.6%) in the power at $VO_2Peak_{2\text{-leg}}$ as a fraction of the jumping power. The same applied to the power at peak fat oxidation that was 3.4±0.4% of power achieved during a vertical jump in both women and men ($p=0.589$). The power (W) at $VO_2Peak_{2\text{-leg}}$ as a fraction of that achieved during a vertical jump was higher ($p=0.002$) in endurance (9.2±0.6%) than power athletes (6.6±0.4%). The power (W) at peak fat oxidation as a fraction of the jumping power was higher ($p=0.007$) in endurance (4.1±0.4%) than in power athletes (2.7±0.3%).

Age-related changes in aerobic and anaerobic power

In table 3 it can be seen that age was the primary determinant of jumping power and $VO_2Peak_{2\text{-leg}}$, both in absolute terms and when normalised to body mass. Sex was the second factor determining absolute jump power and $VO_2Peak_{2\text{-leg}}$, but discipline was more important than sex when jump power and $VO_2Peak_{2\text{-leg}}$ were normalised to body mass (Table 3). For absolute FATmax there was a significant effect of age, but normalised to body mass the FATmax ($mL\cdot kg^{-1}\cdot min^{-1}$) was determined solely by athletic discipline (Table 3).

The aerobic:anaerobic power ratio was not significantly affected by age or sex, but was higher in endurance than power athletes ($p=0.001$; Table 2). However, the ratio of power at FATmax to that at $VO_2Peak_{2\text{-leg}}$ was not affected by age, discipline or sex. The $VO_2Peak_{1\text{-leg}}$:$VO_2Peak_{2\text{-leg}}$ ratio was not significantly affected by age, sex or discipline.

Absolute jumping power (W) (7.4% per decade, $p<0.001$), relative jumping power (W/kg) (9.4% per decade, $p<0.001$, Fig. 2A), absolute $VO_2Peak_{2\text{-leg}}$ ($L\cdot min^{-1}$) (11.2% per decade, $p<0.001$), relative $VO_2Peak_{2\text{-leg}}$ ($mL\cdot kg^{-1}\cdot min^{-1}$) (9.0% per decade, $p<0.01$, Fig. 2B) and $VO_2Peak_{1\text{-leg}}$ ($L\cdot min^{-1}$) (14.2% per decade, $p<0.001$) declined with advancing age.

Discussion

It is widely acknowledged that regular exercise is an effective way to combat or ameliorate the declines in physical function that occur with advancing age. Cross-sectional data from 37-90-year-old master athletes in the present study suggests that both peak anaerobic and aerobic power decline by around 7-14% per decade and that this trajectory did not differ between power or endurance athletes. Even though master athletes perform better than age-matched non-athletes [30], the present results suggest age-related changes in the neuromuscular and cardiopulmonary systems progress at similar rates, regardless of power or endurance competitive specialisations.

The master athletes in the present study were amongst the most athletic Europeans for their age, as reflected by the cohort mean AGP of 82.7 ± 2.2%. To put this into context, a 75-year-old male marathon time of 80% AGP is 3h:46m:53s and the 100 m sprint time is 16:50s. Despite these high achievements, physiological function clearly declined with increasing age.

Power vs. endurance athletes

The counter-movement jump is indicative of maximal anaerobic power [31]. In line with previous observations [15, 20] we observed that the jumping (anaerobic) power per body mass of power athletes was 33% higher than that of endurance runners, reflecting the expected greater muscle power in power than endurance athletes. A novel contribution of our study is that we also collected measurements of peak aerobic power for the same participants and can compare across age and across disciplines. In healthy young adults, $VO_2Peak_{2\text{-leg}}$ during whole body exercise is limited by the oxygen supply to the working muscles [32]. An indication of the extent of the central limitation can be gained from the ratio of one- to two-leg cycling VO_2Peak [29]. The similar ratio in endurance and power athletes suggests that the cardiovascular limitations to two-leg cycling are similar in both athletic groups, despite the very different competitive specialisation of these athletes.

The $VO_2Peak_{1\text{-leg}}$ ($L \cdot min^{-1}$) was similar for endurance and power athletes, despite the leg muscle mass being larger for power athletes than for endurance runners [33]. This is most likely due to the higher oxidative potential per unit muscle mass of endurance runners compared with power athletes [34] to compensate for lower muscle mass. In addition to the higher oxidative capacity per unit muscle mass of endurance athletes [34], we found up to 45% higher rate of fatty acid oxidation per unit body mass in endurance than power athletes at exercise intensities of 30-70% of $VO_2Peak_{2\text{-leg}}$. In line with this, previous studies have shown a significant increase in muscle mitochondrial enzymes and those of fatty acid metabolism

263 following endurance training [35]. A higher rate of fat oxidation, as we observed for endurance athletes, will make the muscle less dependent on glucose metabolism, sparing glycogen and thereby increasing prolonged endurance performance [36]. Such an adaptation is not required in power athletes who rely on anaerobic ATP generation from creatine phosphate and by glycolysis for success in their discipline.

Interestingly, we found that the FATmax was higher in endurance than power athletes in men, but not in women. Nevertheless, like in male (r=0.828, p=0.011) we also observed in female (r= 0.702, p=0.016) endurance athletes a correlation between body mass normalised FATmax and maximal aerobic capacity. Whatever the cause of the absence of a higher FATmax in the female endurance than power athletes, the FATmax appears to be related in both sexes and disciplines with maximal aerobic capacity.

Based on previously published jump data in masters sprinters [15] and the $VO_2Peak_{2\text{-leg}}$ data from endurance runners [42], it was estimated that the proportion of total power that can be generated through aerobic processes is around 30% of the peak anaerobic power [17]. This value is higher than the 9% and 7% we found in endurance and power athletes, respectively. The discrepancy may be due to the previous study deriving maximal anaerobic power data from master sprinters and the $VO_2Peak_{2\text{-leg}}$ data from a different set of specifically-trained master endurance runners, while we calculated this ratio directly from measurements completed in the same individuals. The difference between 2-legged jumping and cycling is also apparent, in that cycling is an alternating limb exercise where every time only one leg produces power and little of the power is gained from musculo-tendinous elasticity, compared to the 2-legged jump [43]. In any case, the aerobic power is only a small fraction of the anaerobic power and this was true regardless of endurance or power training specialisations. The fraction of anaerobic power that can be generated at the peak rate of fatty acid oxidation is even smaller, at 4% for endurance and just 3% for power athletes.

Ageing in power and endurance athletes

We expected that the anaerobic power would be better preserved during ageing in power than endurance athletes, while the $VO_2Peak_{2\text{-leg}}$ would be better preserved in endurance athletes. This is important as throughout life both anaerobic power [2] and $VO_2Peak_{2\text{-leg}}$ decrease with increasing age [3]. In this context it was noted that throughout the life span, the anaerobic power is larger in power athletes [15] and aerobic power larger in endurance athletes [16] than age-matched non-athletes. Similar to previous studies, we found that the rate of decline in peak jump power [15, 20] was similar in power and endurance athletes. The same applied to the decline in $VO_2Peak_{2\text{-leg}}$, which corresponds with other studies that showed that the age-related rate of decline in $VO_2Peak_{2\text{-leg}}$ was similar in endurance runners and non-athletes [42, 44], even though the absolute decline is faster in athletes [16]. This suggests that there is an inherent ageing process that cannot be delayed.

As a consequence of the similar rates of decline in anaerobic and aerobic power in both power athletes and endurance runners, and men and women, the aerobic:anaerobic power ratio remained constant with ageing and higher in endurance than power athletes. This corresponds with the similar relative age-related decrements in running speed records of endurance and power master athletes [17]. This consistent pattern of ageing appears to apply to the performance in many other athletic disciplines, including swimmers [45]. The age-related decrement is not limited to aerobic and anaerobic power, but also applies to the maximal rate of fat oxidation. While older untrained adults have lower rates of fatty acid oxidation than younger adults [37], the ratio of workload at maximal rate of fatty acid oxidation to workload at $VO_2Peak_{2\text{-leg}}$ did not show an age-related decline in either discipline or sex in our study. These proportional declines in work at maximal fatty acid oxidation, and maximal aerobic and anaerobic power suggest that physiological systems determining these parameters age proportionally, irrespective of athletic discipline, or even being an athlete at all.

Such a proportional age-related decline in physiological systems is also reflected by the stable ratio of one-leg to two-leg performance across the ages, irrespective of discipline. This indicates that in both endurance and power athletes the cardiovascular system remains the main limitation of whole body $VO_2Peak_{2\text{-leg}}$ during ageing and that the systems involved in oxygen utilisation age proportionally [16]. Thus in older endurance and power athletes, the oxygen delivering and consuming systems do not violate the principle of symmorphosis that assumes that structures are matched to functional demands [46].

Study limitations

In measurement of $VO_2peak_{2\text{-}leg}$, athletes were stopped when they exceeded by more than 10bpm the age-predicted maximal heart rate. It is possible that athletes did not achieve true maximal oxygen uptake in some cases even if their true maximal heart rate was greater than the methodological constraint that we applied for study governance. However, this bias applied to both sexes and to both power and endurance athletes equally. The present study was a cross-sectional design and recruitment targeted very high performing athletes, which constrained recruitment to relatively low overall sample sizes, although this is commonplace for studies of high performing athletes and the results provide new insights into a model of ageing which is at the peak of physiological performance [7]. While it is possible that the physiological profiles of the athletes are the product of heritable pre-disposition, the intensive exercise training programmes undoubtedly contributed to their outstanding physical capabilities. Furthermore, it is not possible to determine whether the divergent profiles of endurance and power athletes are due to their specific training programmes and/or to heritable factors.

Perspective

Master power athletes appear to exhibit a higher relative anaerobic power and lower relative aerobic power than master endurance athletes. However, the relative (%) annual decline in anaerobic power and aerobic power is similar in both athletic groups. The present data also suggests that during ageing there is a proportional decline in the power at the maximal rate of fat oxidation, irrespective of discipline and sex. It thus appears that there is an inherent, unavoidable (at least by exercise) ageing process that affects cardiopulmonary and neuromuscular systems important for exercise performance. Despite aerobic and anaerobic power declines with advancing age in masters athletes, the benefits of exercise during aging are evident as higher physical function than in age-matched non-athletes [30].

References

1. Degens, H., *The origin of senescence and death; an evolutionary enigma.* Creation Research Society Quarterly, 2008. **44**: p. 280-286.
2. Runge, M., Rittweger, J., Russo, C.R., Schiessl, H.,Felsenberg, D., *Is muscle power output a key factor in the age-related decline in physical performance? A comparison*

of muscle cross section, chair-rising test and jumping power. Clin Physiol Funct Imaging, 2004. **24**(6): p. 335-40.

3. Fleg, J.L.,Lakatta, E.G., *Role of muscle loss in the age-associated reduction in VO2 max.* J Appl Physiol (1985), 1988. **65**(3): p. 1147-51.
4. Degens, H.,Alway, S.E., *Control of muscle size during disuse, disease, and aging.* Int J Sports Med, 2006. **27**(2): p. 94-9.
5. Ingram, D.K., *Age-related decline in physical activity: generalization to nonhumans.* Med Sci Sports Exerc, 2000. **32**(9): p. 1623-9.
6. Hannam, K., Deere, K.C., Hartley, A., Clark, E.M., Coulson, J., Ireland, A., Moss, C., Edwards, M.H., Dennison, E., Gaysin, T., Cooper, R., Wong, A., McPhee, J.S., Cooper, C., Kuh, D.,Tobias, J.H., *A novel accelerometer-based method to describe day-to-day exposure to potentially osteogenic vertical impacts in older adults: findings from a multi-cohort study.* Osteoporos Int, 2017. **28**(3): p. 1001-1011.
7. Hawkins, S.A., Wiswell, R.A.,Marcell, T.J., *Exercise and the master athlete - A model of successful aging?* Journals of Gerontology Series a-Biological Sciences and Medical Sciences, 2003. **58**(11): p. 1009-1011.
8. Cheng, S., Degens, H., Evans, M., Cheng, S.M., Selanne, H., Rittweger, J., Heinonen, A., Suominen, H., Strandberg, T., Alen, M.,Korhonen, M.T., *What Makes a 97-Year-Old Man Cycle 5,000 km a Year?* Gerontology, 2016. **62**(5): p. 508-12.
9. Faulkner, J.A., Davis, C.S., Mendias, C.L.,Brooks, S.V., *The aging of elite male athletes: age-related changes in performance and skeletal muscle structure and function.* Clin J Sport Med, 2008. **18**(6): p. 501-7.
10. Kettunen, J.A., Kujala, U.M., Kaprio, J.,Sarna, S., *Health of master track and field athletes: a 16-year follow-up study.* Clin J Sport Med, 2006. **16**(2): p. 142-8.
11. Pollock, R.D., Carter, S., Velloso, C.P., Duggal, N.A., Lord, J.M., Lazarus, N.R.,Harridge, S.D., *An investigation into the relationship between age and physiological function in highly active older adults.* J Physiol, 2015. **593**(3): p. 657-80.
12. McPhee, J.S., French, D.P., Jackson, D., Nazroo, J., Pendleton, N.,Degens, H., *Physical activity in older age: perspectives for healthy ageing and frailty.* Biogerontology, 2016. **17**(3): p. 567-80.
13. Blair, S.N., Kohl, H.W., Paffenbarger, R.S., Clark, D.G., Cooper, K.H.,Gibbons, L.W., *Physical fitness and all-cause mortality. A prospective study of healthy men and women.* JAMA, 1989. **262**(17): p. 2395-401.
14. Evans, W.J.,Campbell, W.W., *Sarcopenia and age-related changes in body composition and functional capacity.* J Nutr, 1993. **123**(2 Suppl): p. 465-8.
15. Michaelis, I., Kwiet, A., Gast, U., Boshof, A., Antvorskov, T., Jung, T., Rittweger, J.,Felsenberg, D., *Decline of specific peak jumping power with age in master runners.* J Musculoskelet Neuronal Interact, 2008. **8**(1): p. 64-70.
16. Tanaka, H., Desouza, C.A., Jones, P.P., Stevenson, E.T., Davy, K.P.,Seals, D.R., *Greater rate of decline in maximal aerobic capacity with age in physically active vs. sedentary healthy women.* J Appl Physiol (1985), 1997. **83**(6): p. 1947-53.
17. Rittweger, J., di Prampero, P.E., Maffulli, N.,Narici, M.V., *Sprint and endurance power and ageing: an analysis of master athletic world records.* Proceedings of the Royal Society B-Biological Sciences, 2009. **276**(1657): p. 683-689.
18. Ganse, B., Ganse, U., Dahl, J.,Degens, H., *Linear Decrease in Athletic Performance During the Human Life Span.* Frontiers in Physiology, 2018. **9**(1100).

19. Hamill, J., Bates, B.T., Knutzen, K.M.,Sawhill, J.A., *Variations in ground reaction force parameters at different running speeds.* Human Movement Science, 1983. **2**(1): p. 47-56.
20. Grassi, B., Cerretelli, P., Narici, M.V.,Marconi, C., *Peak anaerobic power in master athletes.* Eur J Appl Physiol Occup Physiol, 1991. **62**(6): p. 394-9.
21. Kyröläinen, H.,Komi, P.V., *Neuromuscular performance of lower limbs during voluntary and reflex activity in power- and endurance-trained athletes.* European Journal of Applied Physiology and Occupational Physiology, 1994. **69**(3): p. 233-239.
22. Costill, D.L., Thomason, H.,Roberts, E., *Fractional utilization of the aerobic capacity during distance running.* Med Sci Sports, 1973. **5**(4): p. 248-52.
23. Saltin, B.,Astrand, P.O., *Maximal oxygen uptake in athletes.* Journal of Applied Physiology, 1967. **23**(3): p. 353-358.
24. World Medical Association, *World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects.* JAMA, 2013. **310**(20): p. 2191-4.
25. Cavagna, G.A., *Force platforms as ergometers.* J Appl Physiol, 1975. **39**(1): p. 174-9.
26. Peronnet, F.,Massicotte, D., *Table of nonprotein respiratory quotient: an update.* Can J Sport Sci, 1991. **16**(1): p. 23-9.
27. Mortensen, S.P., Dawson, E.A., Yoshiga, C.C., Dalsgaard, M.K., Damsgaard, R., Secher, N.H.,Gonzalez-Alonso, J., *Limitations to systemic and locomotor limb muscle oxygen delivery and uptake during maximal exercise in humans.* J Physiol, 2005. **566**(Pt 1): p. 273-85.
28. Richardson, R.S., Grassi, B., Gavin, T.P., Haseler, L.J., Tagore, K., Roca, J.,Wagner, P.D., *Evidence of O2 supply-dependent VO2 max in the exercise-trained human quadriceps.* J Appl Physiol (1985), 1999. **86**(3): p. 1048-53.
29. McPhee, J.S., Williams, A.G., Stewart, C., Baar, K., Schindler, J.P., Aldred, S., Maffulli, N., Sargeant, A.J.,Jones, D.A., *The training stimulus experienced by the leg muscles during cycling in humans.* Experimental physiology, 2009. **94**(6): p. 684-94.
30. Korhonen, M.T., Cristea, A., Alén, M., Häkkinen, K., Sipilä, S., Mero, A., Viitasalo, J.T., Larsson, L.,Suominen, H., *Aging, muscle fiber type, and contractile function in sprint-trained athletes.* J Appl Physiol (1985), 2006. **101**(3): p. 906-17.
31. Nummela, A., Alberts, M., Rijntjes, R.P., Luhtanen, P.,Rusko, H., *Reliability and validity of the maximal anaerobic running test.* Int J Sports Med, 1996. **17 Suppl 2**: p. S97-102.
32. Saltin, B.,Calbet, J.A., *Point: in health and in a normoxic environment, VO2 max is limited primarily by cardiac output and locomotor muscle blood flow.* J Appl Physiol (1985), 2006. **100**(2): p. 744-5.
33. Piasecki, J., McPhee, J.S., Hannam, K., Deere, K.C., Elhakeem, A., Piasecki, M., Degens, H., Tobias, J.H.,Ireland, A., *Hip and spine bone mineral density are greater in master sprinters, but not endurance runners compared with non-athletic controls.* Arch Osteoporos, 2018. **13**(1): p. 72.
34. Dubouchaud, H., Butterfield, G.E., Wolfel, E.E., Bergman, B.C.,Brooks, G.A., *Endurance training, expression, and physiology of LDH, MCT1, and MCT4 in human skeletal muscle.* Am J Physiol Endocrinol Metab, 2000. **278**(4): p. E571-9.
35. Coggan, A.R., Spina, R.J., Rogers, M.A., King, D.S., Brown, M., Nemeth, P.M.,Holloszy, J.O., *Histochemical and Enzymatic Characteristics of Skeletal-Muscle in Master Athletes.* Journal of applied physiology, 1990. **68**(5): p. 1896-1901.

36. Van Der Vusse, G.J.,Reneman, R.S., *Lipid Metabolism in Muscle*, in *Comprehensive Physiology*. 2010, John Wiley & Sons, Inc.
37. Sial, S., Coggan, A.R., Carroll, R., Goodwin, J.,Klein, S., *Fat and carbohydrate metabolism during exercise in elderly and young subjects.* Am J Physiol, 1996. **271**(6 Pt 1): p. E983-9.
38. Levadoux, E., Morio, B., Montaurier, C., Puissant, V., Boirie, Y., Fellmann, N., Picard, B., Rousset, P., Beaufrere, B.,Ritz, P., *Reduced whole-body fat oxidation in women and in the elderly.* Int J Obes Relat Metab Disord, 2001. **25**(1): p. 39-44.
39. Abildgaard, J., Pedersen, A.T., Green, C.J., Harder-Lauridsen, N.M., Solomon, T.P., Thomsen, C., Juul, A., Pedersen, M., Pedersen, J.T., Mortensen, O.H., Pilegaard, H., Pedersen, B.K.,Lindegaard, B., *Menopause is associated with decreased whole body fat oxidation during exercise.* Am J Physiol Endocrinol Metab, 2013. **304**(11): p. E1227-36.
40. Oliveira, P.J., Carvalho, R.A., Portincasa, P., Bonfrate, L.,Sardao, V.A., *Fatty Acid Oxidation and Cardiovascular Risk during Menopause: A Mitochondrial Connection?* J Lipids, 2012. **2012**: p. 365798.
41. Calles-Escandón, J., Arciero, P.J., Gardner, A.W., Bauman, C.,Poehlman, E.T., *Basal fat oxidation decreases with aging in women.* J Appl Physiol (1985), 1995. **78**(1): p. 266-71.
42. Wiswell, R.A., Hawkins, S.A., Jaque, S.V., Hyslop, D., Constantino, N., Tarpenning, K., Marcell, T.,Schroeder, E.T., *Relationship between physiological loss, performance decrement, and age in master athletes.* Journals of Gerontology Series a-Biological Sciences and Medical Sciences, 2001. **56**(10): p. M618-M626.
43. Luhtanen, P.,Komi, P.V., *Force-, power-, and elasticity-velocity relationships in walking, running, and jumping.* Eur J Appl Physiol Occup Physiol, 1980. **44**(3): p. 279-89.
44. Pimentel, A.E., Gentile, C.L., Tanaka, H., Seals, D.R.,Gates, P.E., *Greater rate of decline in maximal aerobic capacity with age in endurance-trained than in sedentary men.* J Appl Physiol (1985), 2003. **94**(6): p. 2406-13.
45. Berthelot, G., Len, S., Hellard, P., Tafflet, M., Guillaume, M., Vollmer, J.C., Gager, B., Quinquis, L., Marc, A.,Toussaint, J.F., *Exponential growth combined with exponential decline explains lifetime performance evolution in individual and human species.* Age (Dordr), 2012. **34**(4): p. 1001-9.
46. Hoppeler, H.,Weibel, E.R., *Structural and functional limits for oxygen supply to muscle.* Acta Physiol Scand, 2000. **168**(4): p. 445-56.

Figure Legends

Figure 1. Rates of fatty acid oxidation. Measured during submaximal two-legged cycling and expressed as a function of the %VO_2Peak. Male power athletes (open circles) and endurance runners (closed circles), and female power athletes (open squares) and endurance runners (closed squares) and female. Sex*Discipline interaction ($p=0.019$), reflected by a higher FATmax in male ($p<0.001$), but not female ($p=0.529$), endurance than power athletes.

Figure 2. **Aerobic and anaerobic potential of masters athletes. A)** Absolute peak anaerobic power ($W\cdot kg^{-1}$) decline from the age of 35 years, ($r= -0.713$, $p<0.001$). **B)** VO_2Peak ($mL\cdot kg^{-1}\cdot min^{-1}$) decline from the age of 35 years, ($r= -0.546$, $p<0.001$). **C**) Power output at peak oxygen uptake expressed as a percentage of the peak jump power (W) ($r= 0.103$, $p=0.603$). **D)** Power (W) at FATmax as a percentage of the peak jump power (W) ($r= -0.136$, $p=0.490$). Male endurance runners (closed circles), male power athletes (open circles), female endurance runners (closed squares) and female power athletes (open squares).

Table 1: Characteristics of participants separated by discipline and sex.

Running Discipline	N	Age (years)	Height (m)	BM (kg)	BMI ($kg \cdot m^{-2}$)	AGP (%)
Endurance	8 ♂	62±5	1.74±0.04	66.1±3.6	21.8±1.1	86.3.0±5.5
	11 ♀	58±3	1.63±0.02*	54.9±1.4*	20.7±0.5	79.6±3.8
Power	11 ♂	58±5	1.79±0.03	78.6±2.9†	24.4±0.5†	78.1±4.9
	9 ♀	63±6	1.63±0.02*	61.4±2.7*,†	23.0±0.6†	88.1±3.7

*BM: body mass; BMI: body mass index; AGP: Age-graded performance. Data are shown as mean±SEM. *indicates significant sex difference, †indicates significant difference between disciplines.*

Table 2: Muscle aerobic and anaerobic power of participants separated by discipline and sex

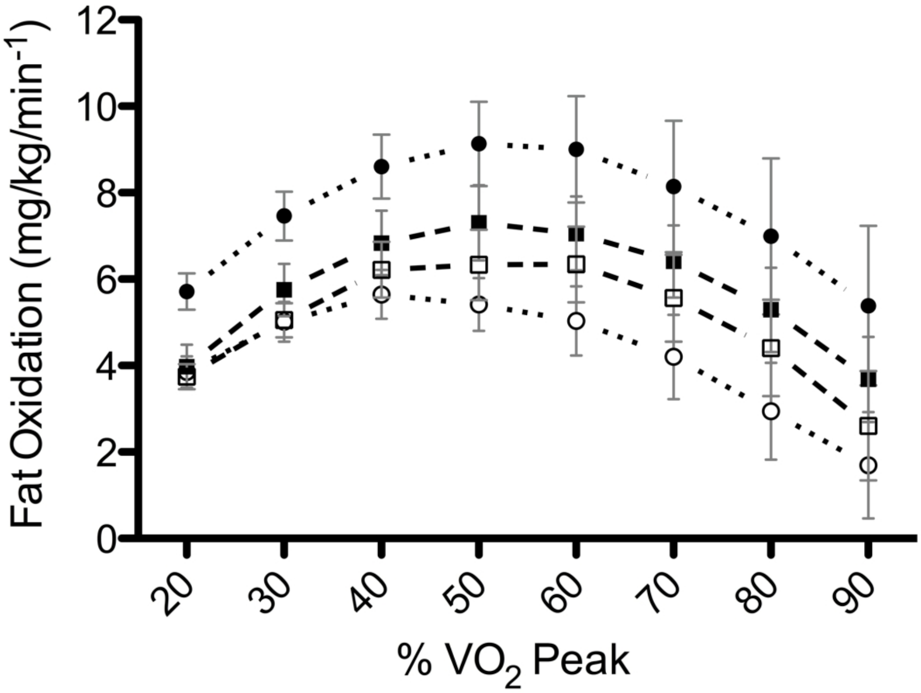
Running Discipline	Sex	JP (W)	JP/BM ($W \cdot Kg^{-1}$)	Velocity take-off ($m \cdot s^{-1}$)	$VO_2Peak_{2\text{-}leg}$ ($L \cdot min^{-1}$)	$VO_2Peak_{2\text{-}leg}$/BM ($mL \cdot kg^{-1} \cdot min^{-1}$)	Power $VO_2Peak_{2\text{-}leg}$ (W)	HR $VO_2Peak_{2\text{-}leg}$ (bpm)	FATmax ($g \cdot min^{-1}$)	FATmax/BM ($mg \cdot kg^{-1} \cdot min^{-1}$)	Power FATmax (W)	Aer:Anaer Power (%)	$VO_2Peak_{1\text{-}leg}$ ($L \cdot min^{-1}$)	Power $VO_2Peak_{1\text{-}leg}$ (W)	$VO_2Peak_{1\text{-}leg}$: $VO_2Peak_{2\text{-}leg}$
Endurance	♂	3081±453 (n=6)	45.3±4.7	2.33±0.12	3.62±0.38	54.2±2.9	259±43	152±8	0.61±0.09	9.12±0.96	149±30	8.94±0.47	2.83±0.62 (n=4)	173±50	0.78±0.04
	♀	1985±179* (n=8)	35.5±2.5	2.10±0.11*	2.35±0.18*	42.9±3.4	188±16*	152±5	0.39±0.04	7.07±0.81	84±12*	9.34±0.92	1.95±0.27 (n=5)	108±12	0.84±0.04
Sprint	♂	4696±432† (n=8)	56.9±3.8†	2.75±0.11†	3.17±0.26	40.0±2.7†	258±28	157±5	0.38±0.03†	4.75±0.30†	126±14	5.98±0.42†	2.25±0.26 (n=5)	123±30	0.79±0.04
	♀	2963±465*,† (n=7)	47.9±7.7†	2.23±0.12*,†	2.54±0.16*	41.7±3.1†	190±12*	164±5	0.38±0.04$^{\blacktriangle}$	6.32±0.82$^{\blacktriangle}$	81±13*	7.24±0.69†	1.83±0.44 (n=4)	93±21	0.73±0.10

JP: Jumping power; JP/BM: Jumping power per body mass; $VO_2Peak_{2\text{-}leg}$/BM*: two-leg* VO_2Peak *per body mass; FATmax: maximal rate of fat oxidation; Aer:Anaer: Aerobic:Anaerobic Power (%);* $VO_2Peak_{1\text{-}leg}$: $VO_2Peak_{2\text{-}leg}$: VO_2Peak of one- *vs* VO_2Peak of two-leg cycling. *Data are shown as mean±SEM. *indicates significant sex difference, †indicates significant difference between disciplines,* $^{\blacktriangle}$*indicates interaction between sex and discipline.*

Table 3: Stepwise linear regression between jumping power, aerobic capacity and rates of fatty acid oxidation with age, sex and discipline.

Jump Power (W)	Jump power per body mass ($W \cdot kg^{-1}$)	VO_2Peak ($L \cdot min^{-1}$)	VO_2Peak per body mass ($mL \cdot kg^{-1} \cdot min^{-1}$)	FATmax ($g \cdot min^{-1}$)	FATmax per body mass ($mg \cdot kg^{-1} \cdot min^{-1}$)
A: 0.391***	A: 0.490***	A: 0.374***	A: 0.279***	A: 0.132*	D: 0.197**
S: 0.652***	D: 0.600***	S: 0.637***	D: 0.364***		
D: 0.789***	S: 0.680***				

*The R-values increase from top to bottom, representing the increased R when an additional factor is included; A: age; S: sex; D: Discipline; FATmax: maximal rate of fat oxidation; *: P < 0.05.**: P < 0.01; ***: P<0.001. Adjusted R-values are presented.*



98x76mm (600 x 600 DPI)

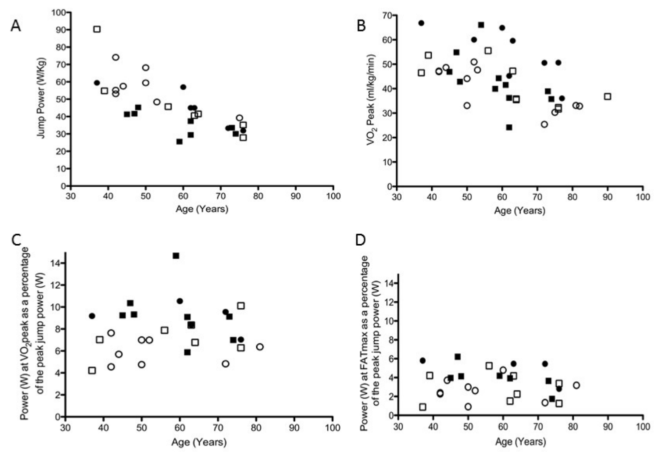


Figure 2

338x190mm (96 x 96 DPI)

SIMILAR RELATIVE DECLINE IN AEROBIC AND ANAEROBIC POWER WITH AGE IN ENDURANCE AND SPRINT MASTER ATHLETES OF BOTH SEXES

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author
The authors have done very good work. The data is valuable because it is very difficult to have such master athletes as subjects. The results are clear and important for practice. All parts of the manuscript are of high scientific work.

> The authors wish to thank the reviewer for their kind appraisal of the quality of our work and its place in the field of literature.

Reviewer: 2

Comments to the Author
This is an interesting manuscript which has studied the effects of age relate declines in in function in a cross-over - type design. It has done this by comparing explosive muscle function and aerobic capability in both sprint and endurance athletes. The paper provides some novel information about ageing that should be published.

> The authors wish to thank the reviewer for their kind appraisal on the novelty of the work presented in our manuscript and their recommendation to publish. Thank you also for the suggestions listed below to improve the quality of the manuscript. All amendments made to the manuscript are highlighted in yellow and a line number given below.

Weakness / Suggestions for improvement
The number of subjects / master athletes is quite low.

> The number of participants is lower than we would normally aim for when studying human physiology and ageing. This may limit the interpretation of the data. However, the participant group is highly specialised and belongs to the top performers of their age. This selection makes recruitment challenging indeed but at the same time we believe that this selection ensured a dataset that offers novel insights into the maximal achievable performance at a given age. Nevertheless, we have given the low number as a limitation in the study limitations section (lines 330-333).

The classification of 800m as a sprint even is dubious. What would happen if these were moved into the endurance category? Or a third category of middle distance athletes created?

If we created categories for power, middle and long distances, the group sizes would become 22, 9 and 8 respectively, and we believe these groups' sizes are too small. However, we do agree with the reviewer that 800 m is not classically defined as a power event and for this reason; we have re-classified ≥800m as endurance and ≤400m as power (Lines 89-91). This has made very little difference to the overall results (with the exception of a newfound sex * discipline interaction for FATmax measures; detail added to result section lines 184-188 and the discussion lines 269-274).
Further to this, we have also re-classified the athletes as "power" and "endurance". The reason for this is that athletes in our cohort competed over multiple events (heptathlon, pentathlon, throwing etc). The AGP presented is for the athletes "best performance" (ie, the highest AGP from all of the performances at this competition).

The rationale for the 1 legged protocol needs to be made much clearer earlier in the paper.

The rationale for this protocol was detailed in the discussion. However, we have added further detail in the methods section (lines 130-135) as suggested.

It would be helpful if the details of each of the athletes (ages, events, physical characteristics etc) in a table (possibly as supplementary material?). This would be of utility to the reader.

We have discussed this amongst authors and decided that we cannot release the individual data as recommended. In the manuscript we have named the competition and the year. If we proceed to also release details of the specific event, ages and height etc., then it would theoretically be possible for somebody to look on the freely-available competitor listings and identify our study participants. This could be classed as a serious breach of participant confidentiality.

Measured maximum / peak heart rates should be included along with the caveat that there were imposed restrictions. How many reached VO2 max without reaching the cut off for max HR?

We agree with this comment. The methodology has been fully described so that readers are aware of the methodological constraints affecting the data. 92% of athletes tested reached (or mostly greatly exceeded) predicted VO2max as determined in *Jones et al., Normal standards for an incremental progressive cycle ergometer test, 1985*.
Further to this, one participant has been excluded from analysis (male, power athlete) due to premature termination of the 2-leg VO2peak test (49% Predicted VO2peak/65% max HR).

The Results section starting at line 24 does not seem to describe cover the main findings of Figure 1 in regard fat oxidation differences between two groups?

An additional line has been added to better explain the findings presented in figure 1. This section now describes that finding that FATmax occurs at a similar %VO2peak between endurance and power athletes, however over the spectrum of exercise intensities, endurance athletes utilise significantly more fatty acid at given exercise intensities from 30-70% VO2peak. Lines 184-188